INCINERATOR DESIGN AND OPERATING CRITERIA

VOLUME II

BIOMEDICAL WASTE INCINERATORS

ONTARIO MINISTRY OF THE ENVIRONMENT
135 St. Clair Avenue West
Toronto, Ontario

OCTOBER 1986

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FOREWORD

The criteria presented in this document have been prepared to assist in the design, assessment and operation of biomedical waste incinerators. The mention of trade names or commercial products in the report does not constitute endorsement or recommendation for use.

This publication is based on a report dealing with the revision of the existing Ontario Ministry of the Environment criteria for incinerator design and operation for pathological waste, and was prepared under contract by Sirman Associates Limited in 1985 and provides specific design parameters as well as operating procedures for biomedical waste incinerators.

This publication is one of the three documents dealing with incinerator design and operating criteria that are being prepared by the Ontario Ministry of the Environment. The other two publications that will be available are "Incinerator Design and Operating Criteria, Volume I (General Criteria)" and "Incinerator Design and Operating Criteria, Volume III (Crematoria)".

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1.0 INTRODUCTION

1.1 General

The criteria expressed in this document supersede those stipulated in the June 1974 Ontario Ministry of the Environment "Criteria for Incinerator Design and Operation [1]" for pathological waste incineration. Part of the need to update the existing criteria has been the change in the composition of waste generated in hospitals and other health care facilities. To reflect current waste composition, the Ontario Ministry of the Environment now uses the term "biomedical" waste to replace the existing definitions of "pathological" and "institutional" wastes. The criteria presented in this document were developed for application to biomedical waste.

1.2 Scope of Document

The topics covered in this document are summarized as follows:

a) characterization of the biomedical waste generated in Ontario, including the component proportion, moisture content, and heating value for each type of biomedical waste;

b) overview of the current technology for the incineration of biomedical waste; and

c) recommendation of design and operating criteria for biomedical waste incinerators.

2.0 BIOMEDICAL WASTE

2.1 Introduction

"Biomedical" waste refers to any waste that includes anatomical waste, pathological waste, infectious waste, hazardous waste, and other waste generated in health care facilities and medical laboratories that require special handling. Previously, the terms "pathological" and "institutional" wastes were used to refer to what is now considered "biomedical" waste.

2.2 Classifications

The Ministry will classify biomedical waste according to the categories presented in Table 1. The Ministry recommends that biomedical waste be segregated and packaged in leakproof, colour-coded plastic bags to facilitate identification, handling, storage, decontamination and transportation.

TABLE 1: MINISTRY CLASSIFICATION AND COLOUR CODING FOR BIOMEDICAL WASTE

Classification	Description	Colour Code
Type A, Class 1	Human anatomical	red
Type A, Class 2	Animal anatomical, infected	orange
Type A, Class 3 a)	Non-anatomical, infected	yellow
b)	Laboratory wastes	yellow
c)	Wastes from DNA work	yellow
Type B, Class 1	Animal anatomical, non-infected	blue

2.3 Collection and Handling in Hospitals and Other Health Care Facilities

Waste collection and handling at most hospitals in Ontario involve the transport of waste by employees from the point of generation (patients' beds, operating rooms, laboratories, etc.) to initial storage points (usually enclosed containers in utility rooms) in each hospital unit. At some hospitals, waste considered to be "contaminated", such as urine containers, histology laboratory cuttings, tubes and bags containing blood, spinal fluid containers, and waste from isolation patients' rooms, are placed in colour-coded plastic bags for separate handling.

To minimize the potential risk of public exposure to hospital waste, some hospitals use rigid containers for transporting the colour-coded bags along routes within the hospital that are accessible to the general public. The use of rigid containers in this situation is considered good practice and is recommended for all hospitals.

Existing waste collection and handling procedures vary from hospital to hospital in Ontario and the practice of colour coding the disposal bags for separate handling is not consistent. **It is therefore recommended that the colour-coding system presented in Table 1 be adopted so that all biomedical waste can be immediately identified. The use of the colour code should be exclusive to biomedical waste to preclude public exposure during general purpose disposal.**

2.4 Waste Generation Rate

2.4.1 Hospitals

Hospital facilities are among the largest generators of solid waste today on a per capita basis. Much of the waste from hospitals comes from the trash basket at the

side of the patient's bed, and includes newspapers, magazines, paperbacks, packaging and discarded flowers. In addition, broken syringes, discarded splints, masks, rubber gloves and broken glass ampoules, etc., generated by other routine activities add to the daily waste stream.

During the last decade, there has been an increasing trend towards the use of disposable products or single-purpose items, which now account for more than one-half of the total hospital waste generated. Nightgowns, sheets, bed pads, pillow cases, etc., which used to be sterilized and reused have been replaced with one-time-use, throw-away articles. Depending on the institution's or hospital's preference for using throw-away materials, the waste generation rate can vary substantially from hospital to hospital.

Pollock[2], and Airan et al.[3] conducted studies on waste generation rates in some U.S. hospitals between 1968-1980. In addition, McCrate[4] carried out a similar study at the Royal Jubilee Hospital located in British Columbia during 1980. The findings of these studies are summarized in Table 2. As can be seen from the Table, the waste generation rates in these studies fall within a range of 1.5-7.5 kg/bed/day.

TABLE 2: SUMMARY OF WASTE GENERATION RATES AT SELECTED HOSPITALS IN THE UNITED STATES AND CANADA

SOURCE	GENERATION RATE (kg/bed/day)
Pollock[2]	
-1968 survey	3.0
-1974 survey	4.1
-1975 survey	4.3
-West Coast Teaching Hospital	3.7
-1978 estimate	7.5
-conclusion of Pollock	3.0-7.5
Airan et al.[3]	
-1980 survey	4.3-5.8
McCrate[4]	
-1980 survey	1.5-3.9

The surveys carried out for these institutions also reflect the situation in Ontario hospitals. This was confirmed in a study carried out by Sirman in 1985 in which he found that the biomedical waste generation rate in Ontario hospitals ranged from 2.3 to 7.7 kg/bed/day[5].

The total biomedical waste stream also includes infectious waste generated from special care beds in surgical rooms, isolation wards and special medical procedure rooms. A 1985 survey sponsored by the Ontario Hospital Association showed that the average-size Ontario hospital generates approximately 0.75 kg/day of infectious waste for each special care bed. This value is based on 75 responses from 164 facilities surveyed.[6]

2.4.2 Medical Laboratories

The waste produced from private and diagnostic laboratories (Type A, Class 3(b) in Table 1) is considered infectious. The waste generation rate is estimated to be 0.2 kg/patient/day and the total quantity of infectious waste from these facilities is higher than that generated in all Ontario hospitals on an annual basis.

Medical laboratory waste contains a very high percentage of plastics (50-60%), the majority of which are non-halogenated. The balance is composed of wet materials such as bodily fluids, blood and used diagnostic reagents, as well as small quantities of paper and cellulose. Most of the medical laboratory waste currently generated is being shipped out of Ontario for disposal. The remaining portion is either incinerated or steam autoclaved and then disposed of in a landfill.

2.4.3 Summary

Depending on an institution's practice of using throw-away materials, the biomedical waste generation rate varies from hospital to hospital. It is recommended that each facility review and document its own practice in order to more accurately determine its waste generation rate. If the actual rate is not available, the Ministry recommends that the following values be used for sizing the capacity of a new biomedical waste incinerator:

<u>Predicted Waste Generation Rate From:</u>

(a) Hospitals

- Total biomedical waste* - 6 kg/bed/day
- Special care waste - 1 kg/special care bed/day

(b) Medical Laboratories

- Total laboratory waste - 0.2 kg/patient/day

* This includes special care waste, but excludes kitchen waste.

3.0 CHARACTERIZATION OF BIOMEDICAL WASTE

3.1 Introduction

This section discusses the physical and chemical characteristics of biomedical waste generated in Ontario, with emphasis on the human and animal anatomical components, moisture content, proportion of plastics and heating value (as fired).

3.2 Physical and Chemical Characteristics

Tables 3A and 3B summarize the properties of the biomedical waste in terms of higher heating value (HHV), moisture content, component weight per cent and bulk density expressed in metric and imperial units, respectively. The breakdown of the waste classifications and colour coding in the tables are based on the Canadian Standards Association guidelines for "Handling of Waste Materials Within Health Care Facilities"-[7]. The ranges of weight percent are based on field measurements as well as data provided by the institutions. The values in Column 7 in each table reflect the weighted HHV range of the waste components (as-fired) under each classification and have been calculated from the data given in columns 3, 4 and 6. The last column (Column 8) represents typical values based on interpretation of actual findings from an Ontario facility.

As can be seen from the wide range of HHV, discretion should be exercised in using the data for the design of a biomedical waste incinerator. A thorough evaluation of the waste should be carried out to identify its characteristics to facilitate the proper design of the incinerator.

TABLE 3A
CHARACTERIZATION OF BIOMEDICAL WASTE (Metric Units)

1	2	3	4	5	6	7	8
WASTE CLASS	COMPONENT DESCRIPTION	TYPICAL COMPONENT WEIGHT PERCENT (AS FIRED)	HHV DRY BASIS (kJ/kg)	BULK DENSITY AS FIRED (kg/m ^{3})	MOISTURE CONTENT OF COMPONENT (WEIGHT PERCENT)	WEIGHTED HEAT VALUE RANGE OF WASTE COMPONENT (kJ/kg)	TYPICAL COMPONENT HEAT VALUE OF WASTE AS FIRED (kJ/kg)
A1 (Red Bag)	Human Anatomical	95-100	18600-27900	800-1200	70-90	1770[a]-8370[b]	2800
	Plastics	0-5	32500-46400	80-2300	0-1	0-2300	400
	Swabs, Absorbants	0-5	18600-27900	80-1000	0-30	0-1400	200
	Alcohol, Disinfactants	0-0.2	25500-32500	800-1000	0-0.2	0-70	50
							3450
A2 (Orange Bag)	Animal Infected Anatomical	80-100	20900-37100	500-1300	60-90	1670-14840	3500
	Plastics	0-15	32500-46400	80-2300	0-1	0-6960	1000
	Glass	0-5	0	2800-3600	0	0	0
	Beddings, Shavings Paper, Fecal Matter	0-10	18600-20900	320-730	10-50	0-1880	1400
							5900
A3 (a) (Yellow Bag)	Guaze, Pads, Swabs Garments, Paper, Cellulose	60-90	18600-27900	80-1000	0-30	7810-25110	15000
	Plastics, PVC, Syringes	15-30	22500-46400	80-2300	0-1	3340-13920	7540
	Sharps, Needles	4-8	140	7200-8000	0-1	6-10	10
	Fluids, Residuals	2-5	0-23200	1000-1020	80-100	0-230	70
	Alcohols, Disinfectants	0-0.2	16200-32500	800-1000	0-50	0-70	30
							22650
A3 (b) (Yellow Bag) Lab Waste	Plastics	50-60	32500-46400	80-2300	0-1	16090-27840	21000
	Sharps	0-5	140	7200-8000	0-1	0-10	0
	Cellulosic Materials	5-10	18600-27900	80-1000	0-15	790-2790	1500
	Fluids, Residuals	1-20	0-23200	1000-1020	95-100	0-230	70
	Alcohols, Disinfectants	0-0.2	25500-32500	800-1000	0-50	0-70	50
	Glass	15-25	0	2800-3600	0	0	0
							22620
A3(c) (Yellow Bag) R & D on DNA	Gauze, Pads, Swabs	5-30	18600-27900	80-1000	0-30	650-8370	2300
	Plastics, Petri Dishes	50-60	32500-46400	80-2300	0-1	16090-27840	21000
	Sharps, Glass	0-10	140	7200-8000	0-1	0-10	0
	Fluids	1-10	0-23200	1000-1020	80-100	0-460	230
							23530
B1 (Blue Bag)	Non-infected Animal Anatomical	90-100	20900-37100	500-1300	60-90	1880-14840	3000
	Plastics	0-10	32500-46400	80-2300	0-1	0-4640	2300
	Glass	0-3	0	2800-3600	0	0	0
	Beddings, Shavings, Fecal Matter	0-10	18600-20900	320-730	10-50	0-1880	1400
							6700

Note 7a (1770kJ/kg) = (0.95)(18600)(1-0.9)
7b (8370kJ/kg) = (1.0)(27900)(1-0.7)

TABLE 3B
CHARACTERIZATION OF BIOMEDICAL WASTE (Imperial Units)

1	2	3	4	5	6	7	8
WASTE CLASS	COMPONENT DESCRIPTION	TYPICAL COMPONENT WEIGHT PERCENT (AS FIRED)	HHV DRY BASIS (BTU/lb)	BULK DENSITY AS FIRED (lb/ft ^{3})	MOISTURE CONTENT OF COMPONENT (WEIGHT PERCENT)	WEIGHTED HEAT VALUE RANGE OF WASTE COMPONENT (BTU/lb)	TYPICAL COMPONENT HEAT VALUE OF WASTE AS FIRED (BTU/lb)
A1 (Red Bag)	Human Anatomical	95-100	8000-12000	50-75	70-90	760[a]-3600[b]	1200
	Plastics	0-5	14000-20000	5-144	0-1	0-1000	180
	Swabs, Absorbants	0-5	8000-12000	5-62	0-30	0-600	80
	Alcohol, Disinfectants	0-0.2	11000-14000	48-62	0-0.2	0-28	20
							1480
A2 (Orange Bag)	Animal Infected Anatomical	80-100	9000-16000	30-80	60-90	720-6400	1500
	Plastics	0-15	14000-20000	5-144	0-1	0-3000	420
	Glass	0-5	0	175-225	0	0	0
	Beddings, Shavings Paper, Fecal Matter	0-10	8000-9000	20-46	10-50	0-810	600
							2520
A3 (a) (Yellow Bag)	Guaze, Pads, Swabs Garments, Paper, Cellulose	60-90	8000-12000	5-62	0-30	3360-10800	6400
	Plastics, PVC, Syringes	15-30	9700-20000	5-144	0-1	1440-6000	3250
	Sharps, Needles	4-8	60	450-500	0-1	3-5	5
	Fluids, Residuals	2-5	0-10000	62-63	80-100	0-11	30
	Alcohols, Disinfectants	0-0.2	7000-14000	48-62	0-50	0-28	15
							9700
A3 (b) (Yellow Bag) Lab Waste	Plastics	50-60	14000-20000	5-144	0-1	6930-12000	9000
	Sharps	0-5	60	450-500	0-1	0-3	0
	Cellulosic Materials	5-10	8000-12000	5-62	0-15	340-1200	650
	Fluids, Residuals	1-20	0-10000	62-63	95-100	0-100	30
	Alcohols, Disinfectants	0-0.2	11000-14000	48-62	0-50	0-28	20
	Glass	15-25	0	175-225	0	0	0
							9700
A3(c) (Yellow Bag) R & D on DNA	Gauze, Pads, Swabs	3-30	8000-12000	5-62	0-30	280-3600	1000
	Plastics, Petri Dishes	50-60	14000-20000	5-144	0-1	6930-12000	9000
	Sharps, Glass	0-10	60	450-500	0-1	0-6	0
	Fluids	1-10	0-10000	62-63	80-100	0-200	100
							10100
B1 (Blue Bag)	Non-infected Animal Anatomical	90-100	9000-16000	30-80	60-90	810-6400	1400
	Plastics	0-10	14000-20000	5-144	0-1	0-2000	1000
	Glass	0-3	0	175-225	0	0	0
	Beddings, Shavings, Fecal Matter	0-10	8000-9000	20-46	10-50	0-810	600
							3000

Note 7a (760BTU/lb) = (0.95)(8000)(1-0.9)
7b (3600Btu/lb) = (1.0)(12000)(1-0.7)

Based on the data from Table 3A, the typical higher heating values for each type of biomedical waste are summarized in Table 4. It can be seen that yellow-bag waste generally has a heating value of 21,000 kJ/kg or greater. All other colour-coded bags are 6,700 kJ/kg or less and may require the use of auxiliary fuel when being incinerated.

TABLE 4: TYPICAL HIGHER HEATING VALUES FOR VARIOUS BIOMEDICAL WASTE CLASSIFICATIONS (as fired)

Classification	Colour Code	Typical HHV (kJ/kg)
Type A, Class 1	Red	3,450
Type A, Class 2	Orange	5,900
Type A, Class 3 a)	Yellow	22,650
b)	Yellow	22,620
c)	Yellow	23,530
Type B, Class 1	Blue	6,700

It may be possible to blend different colour-coded bags of waste to modify the overall composition of the waste charged into the incinerator. In this way, waste with a low heat content can be combined with waste of higher heat content to form a waste capable of self-sustaining combustion. If all waste types in Table 4 are combined equally, the average HHV would be 13,877 kJ/kg, which is higher than that of typical municipal solid waste (11,140 kJ/kg). However, the possibility of blending must be evaluated on a case-by-case basis.

The typical chemical composition of animal anatomical waste and the associated combustion data are given in Table 5. It should be noted that this is only one type of biomedical waste and does not include components such as plastics and cellulose gauzes, which have a higher heat content than anatomical waste.

TABLE 5: CHEMICAL COMPOSITION OF ANIMAL ANATOMICAL WASTE AND COMBUSTION DATA
(Derived from reference)[8]

Ultimate Analysis (whole dead animal)

Constituent	As charged % by weight	Ash and moisture free combustible % by weight
Carbon	14.7	50.80
Hydrogen	2.7	9.35
Oxygen	11.5	39.85
Water	62.1	-
Nitrogen	Trace	-
Mineral (ash)	9.0	-

Dry combustible empirical formula - $C_5 H_{10} O_3$

Combustion data
(based on 1 kg of dry ash-free combustible)

Constituent		Quantity kg	Volume Nm^3
Theoretical air		7.03	5.77
40% sat at 15.5°C		7.06	5.81
Flue gas with	CO_2	1.86	1.00
theoretical	N_2	5.40	4.57
air 40%	H_2O formed	0.76	1.00
saturated	H_2O air	0.03	0.04
Products of combustion total		8.05	6.61

Gross Heat of combustion 20,471 kJ/kg

3.3 Microbiological Characteristics

Care should be exercised when handling biomedical waste primarily due to its infectious or hazardous nature. Testing was carried out by Barbeito et al. to evaluate whether sterilization, or a total pathogen kill, could be achieved by incineration[9]. His research indicates that destruction of

micro-organisms within the incinerator depends on the temperature and time exposure. Barbeito indicates that any emission of micro-organisms from the incinerator could be attributed to insufficient retention time and temperature as a result of the following conditions:

- initial charging of the incinerator before operating temperatures are achieved;
- failure to preheat the refractory lining;
- temperature fluctuations caused by intermittent use;
- exceeding design linear velocities, thereby reducing the retention time;
- charging beyond incinerator capacity; and
- excessive moisture content of the waste.

Other factors such as the type of refractory lining, the positioning and number of burners, and the precision of temperature controlling devices, can also have a significant bearing on the effectiveness of sterilization.

Barbeito recommends that the following measures be taken to ensure the complete destruction of micro-organisms in the incinerator:

a) the minimum temperatures in the primary and secondary chambers should be maintained at no less than 760°C (1400°F) and 870°C (1600°F), respectively;

b) a minimum of one-half hour should be used as a preheat period for the secondary chamber prior to feeding the waste into the incinerator;

c) if an incinerator is not operated continuously, only non-infectious waste should be incinerated initially after the unit is fired up; infectious

waste should only be fed into the incinerator after the secondary chamber has been on for one-half hour; and

d) each incinerator should be tested with bacterial spores, the most resistant micro-organisms, to establish the minimum temperatures required to achieve complete sterilization.

The destruction of micro-organisms in the incinerator ash also depends on temperature and time exposure. It is therefore desirable to discharge the ash on a batch basis at the end of each incineration cycle (typically 4-6 hours) to provide a long solids retention time in the primary chamber in order to achieve complete destruction of the micro-organisms.

4.0 INCINERATION TECHNOLOGY FOR BIOMEDICAL WASTE

This section presents a brief summary of the technology available for biomedical waste incineration based on published literature as well as information obtained from incinerator manufacturers and suppliers.

4.1 Types of Incinerators

There are basically three types of incinerators that are available for the incineration of biomedical waste, namely:

- multiple-chamber (retort and in-line);
- controlled-air; and
- rotary kiln.

In the past, the most prevalent type of incinerator used for the disposal of biomedical waste has been the multiple-chamber unit. However, since the mid 1970's, preference has shifted to the controlled-air design. In addition, the rotary kiln type has also been used in recent years to incinerate biomedical waste in some hospitals in the United States[11].

Regardless of the type of incinerator, it must provide sufficient temperature, turbulence and retention time to ensure complete destruction of the biomedical waste. The following sections describe the three main types of incinerators in more detail.

4.1.1 Multiple-chamber Incinerator

The multiple-chamber incinerator has a minimum of three chambers, passes, or zones. The primary chamber is equipped with a solid hearth (either hot or cold type) complete with a lip (or trough) about 5.0 cm deep to

contain fluids. A hot hearth is constructed of conducting refractory and offers significant heat conductivity and a more complete burn. Open grate hearths cannot contain fluids and are therefore not suitable for use in biomedical waste incinerators.

The retort incinerator is characterized by 90-degree directional turns of the gas flow laterally and vertically. The combustion gases may be directed under the solid hearth on which wastes are disposed of, or to the secondary chamber. The flow of hot gases under the solid hearth is advantageous and desirable because it allows for heat transfer to the solid hearth which will aid in combustion in the primary chamber, and helps to ensure sterilization of the resulting ash. A cutaway view of a typical retort incinerator is shown in Figure 1.

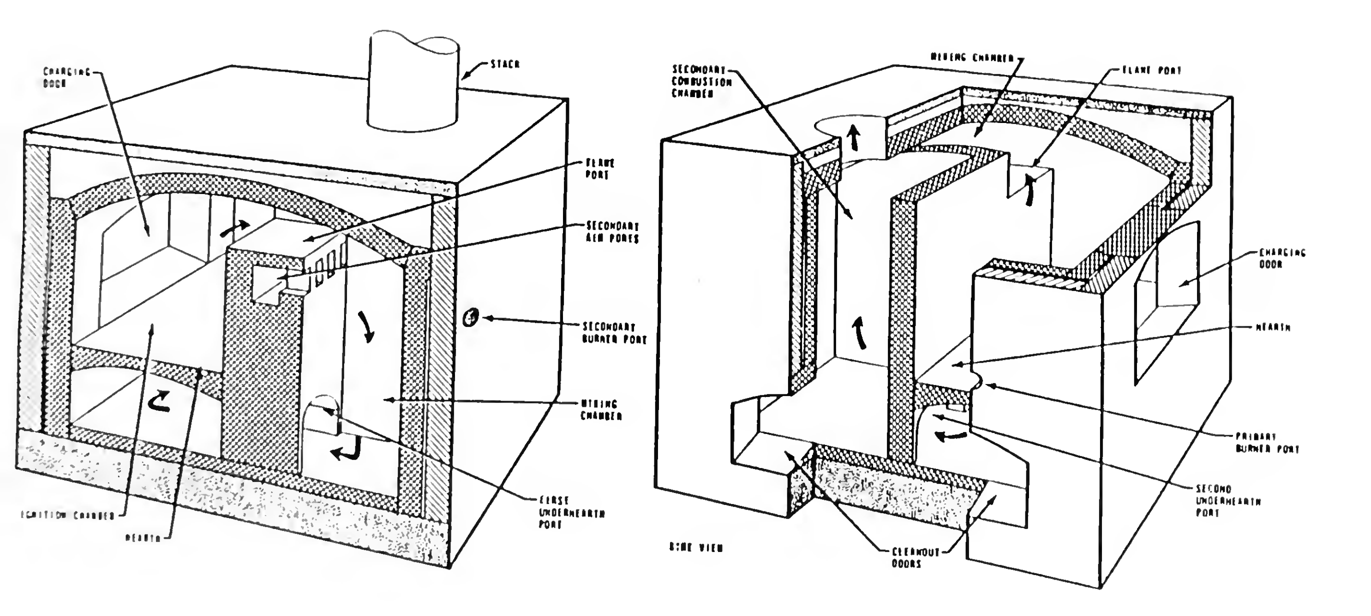


FIGURE 1: RETORT TYPE MULTIPLE-CHAMBER PATHOLOGICAL WASTE INCINERATOR [8]

The in-line incinerator is usually larger and combustion gas flow is directed through 90-degree turns in the vertical plane only. Unlike the retort unit, the in-line incinerator is usually equipped with a grate (Figure 2), which renders it unsuitable for wastes with a high fluid content. However, the in-line incinerator can be equipped with a separate hot hearth to accommodate biomedical waste incineration.

Multiple-chamber incinerators have been widely used for the destruction of pathological waste. The basic unit is capable of operating at a high combustion temperature and appropriate controls can be provided to contain fats and other liquids until burnout is achieved. It can also be operated on an intermittent basis, which makes it particularly amenable to the incineration of anatomical and infectious wastes which are seldom generated in large quantities by a single facility.

Multiple-chamber incinerators operate in the excess air mode with an overall excess air range of 150-400 percent. Combustion air is normally provided by natural draft and admitted through manually-operated ports. Barometric dampers are used to control the draft and thus the quantity of air induced into the incinerator.

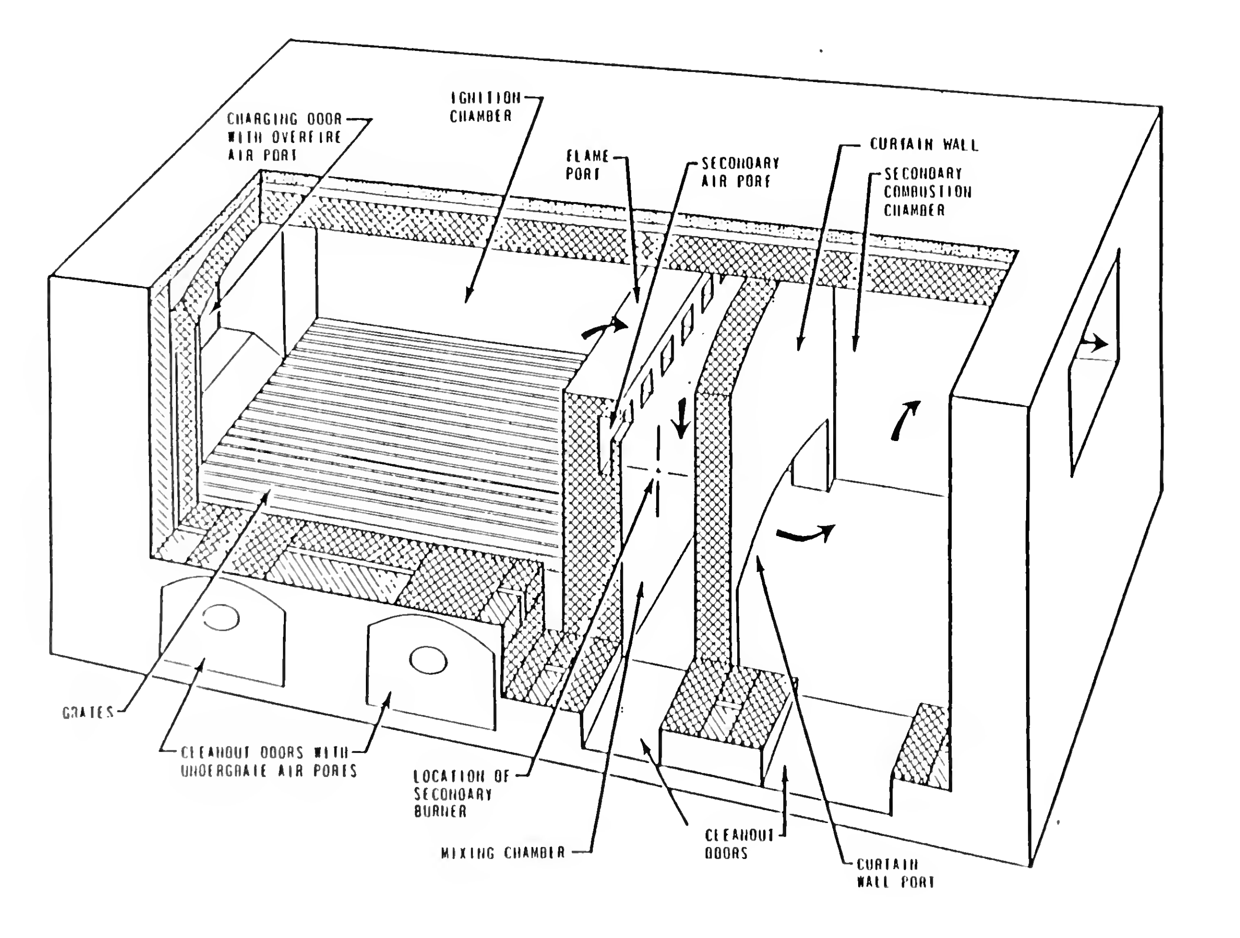


FIGURE 2: IN-LINE TYPE MULTIPLE-CHAMBER INCINERATOR [8]

An important consideration in the operation of multiple-chamber incinerators is that the waste should be charged across the hearth in a single layer to provide for maximum exposure of surface area to the burner flame. This is best accomplished by the frequent charging of small amounts of waste to the incinerator.

When multiple-chamber incinerators were in widespread use, the composition of pathological waste designated for incineration was not highly variable. The waste had a higher heating value in the order of 2320 kJ/kg (1000 BTU/lb) and required appreciable quantities of auxiliary fuel to sustain combustion in the incineration process. Under these conditions, steady heat input of the burners throughout the total duration of the burn cycle was necessary for complete destruction of the waste.

The physical and thermal characteristics of today's biomedical waste have become much more complex, thereby placing severe limitations on the use of multiple-chamber incinerators. The design is still suitable for burning pathological waste (e.g. animal carcasses) that has a slow heat release rate and a relatively constant oxygen demand. However, most biomedical waste generated today has a much higher heat release rate and greater oxygen demand fluctuation during incineration, due to its higher plastics content.

As a result, the use of a damper to control the air required for the incineration of biomedical waste is not efficient due to its slow response. This leads to incomplete combustion causing excessive emissions and opacity problems. In addition, the need for a steady heat input from the burners to maintain the temperature of the large volume of excess air has, from an energy

cost viewpoint, placed the multiple-chamber incinerator in a non-competitive position compared with other incinerator designs requiring less excess air.

4.1.2 Controlled-air Incinerators

The controlled-air incinerator, also referred to as the modular incinerator, makes use of a two-stage combustion process. It usually consists of a primary chamber, followed by a secondary combustion chamber (Figure 3). The mode of operation of the primary chamber is used to classify controlled-air incinerators as either excess-air or starved-air (sub-stoichiometric) units. The differences in these two modes of operation are summarized below:

(a) <u>Starved-air incinerator</u>

- provides less than the theoretical (stoichiometric) quantity of air in the primary chamber (typically 30 to 80% of stoichiometric requirements);
- pyrolysis gases are formed in the primary chamber;
- provides excess air in the secondary or after-burner section to complete combustion (total excess air in the afterburner section varies between 40-250%).

(b) <u>Excess-air incinerator</u>

- provides air in the primary chamber in excess of that required for combustion (typically 60-200% excess air);
- no pyrolysis gases leave the primary chamber;
- promotes almost complete combustion in the primary chamber (in the order of 90-95%);

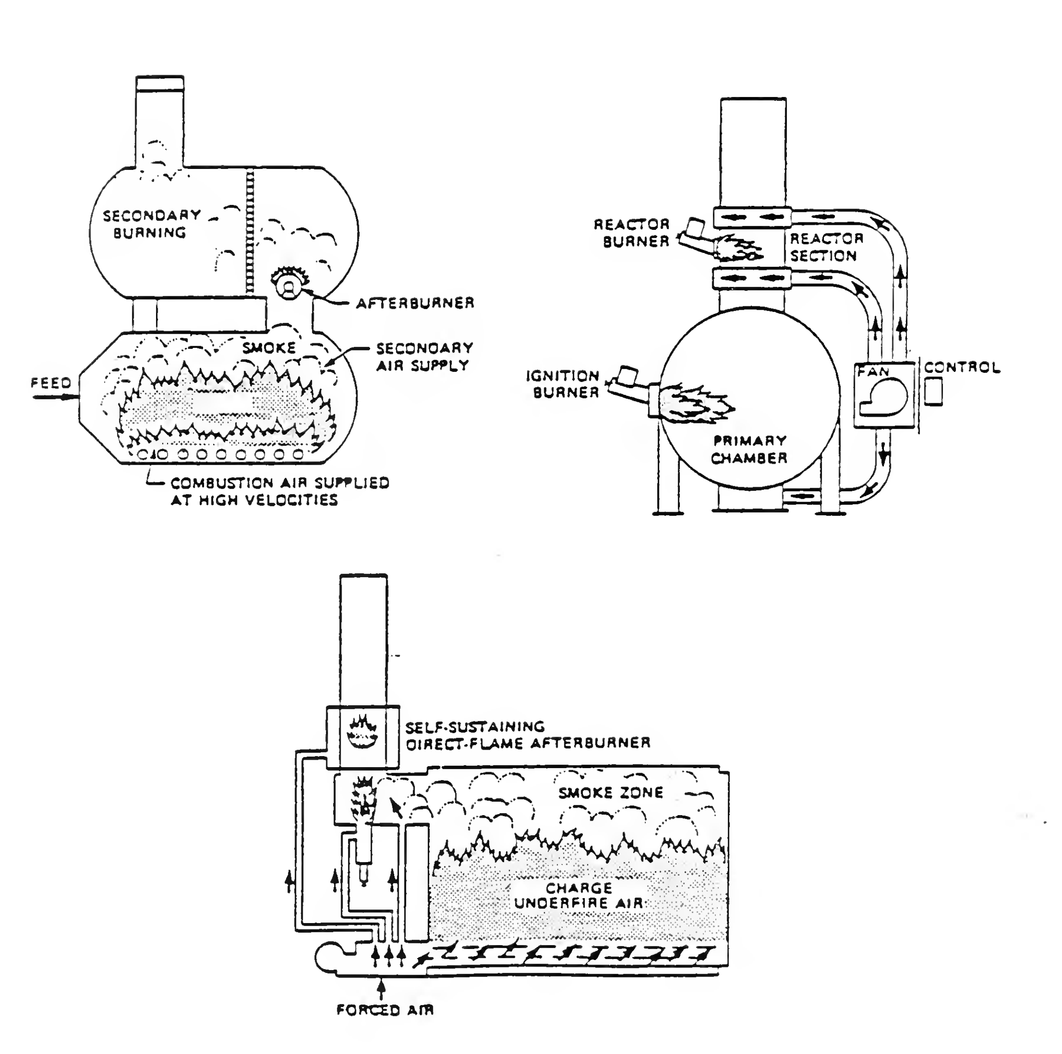


FIGURE 3: TYPICAL CONFIGURATIONS OF CONTROLLED AIR INCINERATOR [10]

- gas-phase combustion is completed in the secondary chamber with additional air as required.

Of the two types of controlled-air incinerators, the starved-air unit appears to be more widely used. The success of the starved-air design has, in large part, been due to its ability to reduce the entrainment of particulate matter in the flue gas. This is attributed to the minimum disturbance of the fuel bed and a slower rate of volatilization, which reduces fly ash formation and generates a lower uplift velocity.

Controlled-air incinerators are manufactured by several vendors as standard models that can be modified to suit the specific needs of a customer. Units under 340 kg/h (750 lb/hr) are normally batch fed using a hopper/ram assembly or double ram system to minimize the infiltration of air into the primary chamber during charging. Larger units are usually provided with a continuous waste charging system, such as a screw feeder.

The temperature in the primary chamber is usually maintained in the range of 400-870°C (750-1600°F), whereas the secondary chamber may operate at a temperature as high as 1100°C (2010°F). Retention time for the gas phase in the secondary chamber is in the order of 0.5 to over 1.0 second.

The major difference between the controlled-air and multiple-chamber incinerators relates to the amount of combustion air supplied and the manner in which this is introduced into the unit. In a controlled air incinerator, the rate of combustion air supplied to each chamber is controlled by temperature. Automatic fan

damper positioning is normally used to control the air-flow and, therefore, temperature in each chamber. The controlled-air concept is particularly attractive when incinerating waste materials that exhibit a wide variation in composition, such as non-anatomical bio-medical waste. It is better than the multiple-chamber incinerator in that it provides higher combustion efficiency, faster response to temperature fluctuations, and easier operating control.

4.1.3 Rotary Kiln Incinerator

The key component of the rotary kiln incinerator is a refractory lined cylindrical shell, mounted at a slight incline from the horizontal plane and usually followed by an afterburner section to ensure complete combustion (Figure 4).

Feeding systems for the rotary kiln include a ram feed mechanism and a charging auger. The ram feed mechanism for waste charging can be designed to provide manual feed or a hopper and guillotine-door arrangement. The charging auger is usually arranged to receive the waste from an overhead hopper. The compaction of waste by the auger at the feed point of the kiln occurs as a result of the reduction in casing diameter and minimizes the potential for burnback into the waste. For additional burnback protection, a water spray fire-protection system can also be included in the design.

The length to diameter (L/D) ratio for rotary kilns ranges from 2:1 to 10:1, and rotational speeds range from 0.3 to 1.5 metres per minute at the kiln periphery. Speed of rotation can be varied to maintain adequate solids retention time in the kiln to ensure good burnout of the waste. Residence times vary from a few seconds

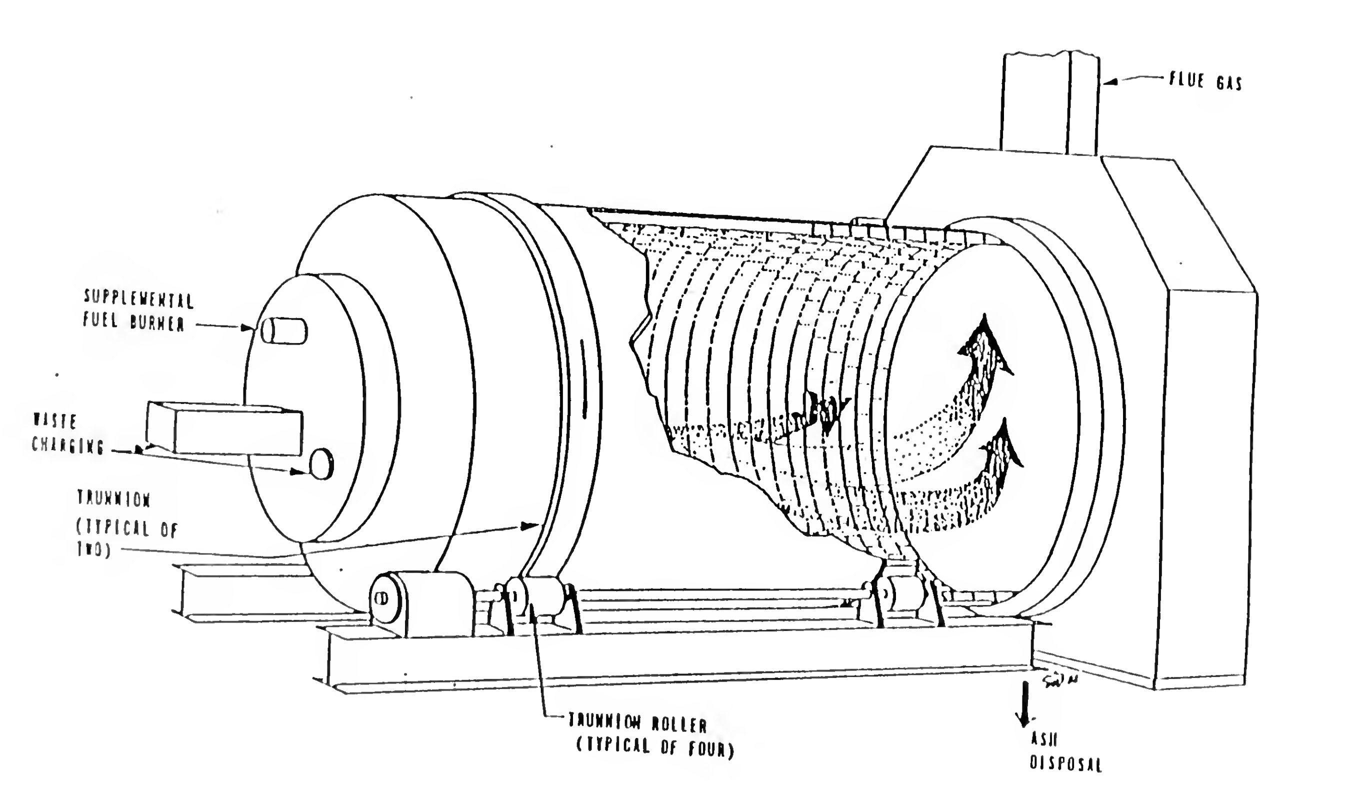


FIGURE 4: THE ROTARY KILN [12]

for gases, to a few hours for solids. Typical operating temperatures for rotary kiln incinerators are in the range of 800-1200°C (1470-2190°F). Since rotary kilns are normally totally refractory-lined and have no exposed metallic parts, they can be operated at high incineration temperatures with minimal corrosion effects.

Rotary kilns have been successfully applied to various industrial operations, including pulp and paper bisulphite mills and cement plants. The technology is well suited for the incineration of a wide variety of liquids and solids, and is particularly amenable to the destruction of wastes that are difficult to thermally degrade, since temperatures in excess of 1400°C (2550°F) can be achieved. In addition, rotary kilns can accommodate the direct charging of bulk containers without preparation. Although the use of rotary kilns in the destruction of biomedical waste is relatively new, they do offer potential application in this area.

There are some disadvantages in the use of rotary kiln technology for waste incineration, such as relatively high particulate loadings in the exhaust gases due to high turbulence, and low thermal efficiency resulting from air leakage or tramp air via the kiln end seals.

4.2 Conclusions

Of the three types of incinerators, the controlled-air unit is currently the most widely accepted system for the incineration of biomedical waste. The application of rotary kiln technology for this purpose is still relatively new, and is therefore less attractive due to lack of operating

experience. However, based on their performance in other applications, rotary kilns offer potential for the efficient destruction of biomedical waste in the future. The multiple-chamber incinerator, as originally designed, is no longer considered suitable to handle the whole range of biomedical waste currently generated in the hospitals, other health care facilities and medical laboratories. It is, however, still useful for the destruction of waste that has little variation in composition, such as anatomical waste.

5.0 DESIGN AND OPERATING CRITERIA FOR BIOMEDICAL WASTE INCINERATORS

5.1 General

The design criteria for the incineration of biomedical waste are presented in this section and are discussed under the following headings:

- Feed System
- Primary Chamber
- Secondary Chamber
- Turbulence
- Combustion Air
- Burners
- Process Monitoring/Control
- Quenching
- Ash Disposal
- Operating Procedure
- Incinerator Stack

5.2 Feed System

5.2.1 All feed systems should be designed to prevent leakage of liquids that may be contained in the waste and should be sloped towards the opening of the incinerator.

5.2.2 Provisions should be made to disinfect the hopper sides and containers when mechanical feed systems are used. Cleaning fluids should be drained to a controlled area or container and properly disposed of.

5.2.3 Mechanical feed systems should be interlocked with the charging mechanism to facilitate lock-out of the waste feed if the temperature in the secondary chamber falls below 1000°C (1830°F).

5.2.4 Automated mechanical feed systems are desirable to maintain steady operation.

5.3 Primary Chamber

5.3.1 The rate at which waste is fed into the incinerator is critical to the successful operation of the unit because the feed rate determines the heat release rate of the biomedical waste and the size of the primary chamber. Biomedical waste contains low density, high heating value wastes (e.g. plastics) as well as high density, low heating value wastes (e.g. tissue, bones). Therefore, the primary chamber should be sized to accommodate the variation in the waste composition.

5.3.2 The volume of the primary chamber should be designed to allow for a total heat release rate of between 445,000 $kJ/h/m^3$ (12,000 $BTU/hr/ft^3$) and 930,000 $kJ/h/m^3$ (25,000 $BTU/hr/ft^3$). A heat release rate of over 930,000 $kJ/h/m^3$ (25,000 $BTU/hr/ft^3$) is not recommended for use in the design as this may lead to uncontrolled conditions, resulting in high particulate emissions, poor micro-organism destruction and the discharge of incomplete combustion products to the environment.

5.3.3 The hearth area should be designed to allow a burning rate of 58.5-68.5 kg/h/m^2 (12-14 lb/hr/ft^2).

5.3.4 The primary chamber should be designed to operate continuously under negative pressure to prevent fugitive emissions.

5.3.5 Temperature in the primary chamber should be maintained in the range of 400-760°C (750-1400°F). Avoiding temperature peaks above 760°C will minimize excursions in gas velocities, thereby reducing ash carry-over and particulate emissions.

5.3.6 The external casing of the chamber should be designed to maintain a maximum temperature of 70-90°C (160-195°F). This can be accomplished with the use of refractory and/or insulation materials. Where appropriate, an expanded metal shield or other suitable means of shielding should be installed for the protection of personnel.

5.3.7 The primary chamber hearth should have an adequate grease containment lip at the opening to prevent escape or leakage of fluids from the chamber. The lip should be a minimum of 5 cm (2 inches) deep.

5.3.8 A "hot hearth" is recommended for use in all primary chambers where economically feasible.

5.4 Secondary Chamber

5.4.1 The temperature in the secondary chamber should be designed for a minimum of 1100°C (2010°F) with an operating temperature of not less than 1000°C (1830°F) at all times.

5.4.2 The incinerator should be designed to provide no less than 6% residual oxygen in the flue gas exhaust from the secondary chamber.

5.4.3 The secondary chamber should be designed for a gas residence time of not less than 1 second at 1000°C (1830°F). This residence time is to be based on the volume of the secondary chamber from the flame front to the location of the temperature sensing device.

5.4.4 The temperature in the secondary chamber should be controlled by a thermocouple or other temperature sensor located at a point representing 1 second retention time at the exit of the secondary chamber or at the breeching. The thermocouple should be connected to a system to provide automatic temperature control and it should also regulate the modulating secondary chamber burner.

5.4.5 The refractory surface of the secondary chamber should be heated over a minimum period of half an hour, prior to feeding waste into the incinerator, to ensure optimum conditions for the destruction of micro-organisms.

5.4.6 The external casing of the secondary chamber should be designed to maintain a maximum temperature of 70-90°C (160-195°F) by means of insulation and refractory. For protection of personnel, an expanded metal shield or other suitable means of protection should also be installed on the casing.

5.5 <u>Turbulence</u>

5.5.1 Gas turbulence is an important parameter in the design of incinerators and can be achieved by high combustion gas velocity, tangential air injection, abrupt changes in flow direction, and the installation of combustion gas restrictions (e.g. orifices, checkerwork, or baffles).

5.5.2 Turbulence is difficult to quantify; however, use of the Reynolds number (Re) has been suggested to provide an indication of the gas phase turbulence in the incinerator. An example of the calculation of Re is provided in Appendix B.

5.5.3 The calculated Reynolds number in the secondary chamber should be over 10,000 to ensure turbulent flow.

5.6 <u>Air Requirements</u>

5.6.1 For starved-air incinerators, air into the primary chamber should be supplied at 30 to 80% of that required for stoichiometric combustion.

5.6.2 The air supply in the secondary chamber of all incinerators should be able to provide excess air at 40 to 250% of that theoretically required during the peak burning rate.

5.6.3 The combustion air supply should be automatically adjustable with a Temperature Recorder Control system to maintain the set temperatures in the primary and secondary chambers of the the incinerator.

5.7 Burners

5.7.1 The burners must be able to maintain a stable flame throughout the range of pressures, input rates, and fuel/air ratios experienced in the primary and secondary chambers.

5.7.2 The burners should be designed to supply a minimum of 80% of the total heat input of the incinerator design capacity. The burners must also be capable of modulating down to 15% of the total heat input requirement.

5.7.3 The burner(s) in the primary chamber should be:

- located at a downward angle to provide maximum impingement of the flame onto the wastes. The alignment of the burner(s) should not allow the flame to impinge on the refractory walls or on other burner(s);

- set to maintain a temperature of 400-760°C (750-1400°F) in the primary chamber once the burn cycle is initiated;

- constructed with a sealed casing to eliminate the flow of tramp air into the chamber.

5.7.4 The burner(s) in the secondary chamber should be:

- mounted to promote thorough mixing throughout the whole chamber. The alignment of the burner(s) should not allow the flame to impinge on the refractory walls or on other burner(s);

- designed to automatically lock out the primary chamber charging mechanism in the event of burner(s) failure;

- set to maintain a temperature of not less than 1000°C (1830°F) in the secondary chamber at all times;

- fully modulating with a low "hold fire" setting to ensure a flame throughout the incineration cycle.

5.8 Process Monitoring/Control

5.8.1 One, or preferably two, viewports should be installed in the primary chamber immediately behind the burners to facilitate visual inspection of the burn. The location should be slected to reduce particulate impingement, so that the viewport will remain relatively clean.

5.8.2 A Temperature Recorder/Controller (TRC) should be used to control primary and secondary temperatures by:

- turning off or reducing heat input from the burners;
- turning off, throttling back, or increasing the air supply; and
- turning on the quench water system, where used.

The TRCs should provide a graphical recording of the temperature variations and feedback of the operating fluctuations.

A TRC should be used to monitor the temperature at the exit of the primary chamber and also control the air supply to the primary chamber and its auxiliary burners. A second TRC should be installed to monitor the temperature at the exit of the secondary chamber or at the base of the stack and also to control the secondary air supply and its auxiliary burners.

5.8.3 All incinerators should be equipped with continuous total hydrocarbon or carbon monoxide monitoring equipment. An opacity meter should also be provided in the incinerator stack.

5.9 Quenching

5.9.1 A water quench system should be provided in the primary chamber of the incinerator to prevent the temperature from developing into runaway conditions and/or to reduce flue gas temperatures at the exit of the secondary chamber.

5.9.2 The quench system should be activated by the primary chamber TRC and sized to reduce the temperature in the primary chamber by 200°C (390°F) within 60 seconds.

5.10 Ash Disposal

5.10.1 Ash resulting from the incineration of biomedical waste may contain significant quantities of sharps, needles and glass; therefore, care should be exercised in the removal and disposal of incinerator ash.

5.10.2 The incinerator ash should be wetted prior to handling to minimize the potential for generating airborne dust.

5.10.3 All personnel handling the ash should wear or use dust masks, gloves, and protective clothing as a safety precaution.

5.10.4 The incinerator ash should be stored in enclosed containers and transported to an approved landfill site for disposal.

5.11 Operating Procedure

5.11.1 Waste should not be charged into the incinerator during the start-up period until the refractory surface of the secondary chamber has been heated up to the operating temperature.

5.11.2 The initial charges to the incinerator should be non-infectious waste; infectious waste should be fed later in the incineration cycle.

5.11.3 The waste should be weighed and logged prior to charging to ensure that the design feed rate is not exceeded and to maintain a record of the quantities of waste processed.

5.11.4 Incinerator operators should be properly trained and be familiar with all the manufacturer's operating procedures for the unit.

5.11.5 The ash in the primary chamber should be discharged on a batch basis at the end of each incineration cycle to ensure complete destruction of the micro-organisms.

5.12 Incinerator Stack

5.12.1 For natural draft systems, calculations for stack design should be based on a gas temperature of 1000°C (1830°F). If substantial heat losses through the stack are expected, such losses should be taken into account in determining the average stack temperature and the available draft.

The stack height should be calculated to provide a minimum available draft of 6.3 mm (0.25 in.) water gauge (W.G.) at the breeching. The latter is an absolute minimum draft provision for all natural draft biomedical waste incinerators and must result in a draft of at least 2.5 mm (0.1 in.) W.G. at the burner air inlets. Perry's Chemical Engineers' Handbook[13] outlines procedures for calculating stack draft.

6.0 CONCLUSIONS

The basic principles of good incinerator design have been used to develop the foregoing recommendations. New ideas or designs which fulfill the temperature, retention time, turbulence and other requirements stipulated in this document are encouraged and will be evaluated according to these basic principles. As technical advances and practical observations provide more information, the criteria will be revised accordingly.

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APPENDIX A:

HEAT AND MATERIAL BALANCE SAMPLE CALCULATIONS

APPENDIX A:
HEAT AND MATERIAL BALANCE SAMPLE CALCULATION

A heat and material balance is an important part of designing and/or evaluating incinerators. The procedure entails a mathematical evaluation of the input and output conditions of the incinerator. It can be used to determine the combustion air and auxiliary fuel requirements for incinerating a given waste, and/or to determine the limitations of an existing incinerator when charged with a known waste.

EXAMPLE: An incinerator is to be designed to incinerate a mixture of 30% red bag and 70% yellow bag (with a PVC content of 4%) biomedical waste. Throughput is to be 100 kg/h of waste. The auxiliary fuel is natural gas; the waste has been ignited; and the secondary burner is modulating. Design requirements are summarized as follows:

- secondary chamber temperature: 1100°C
- flue gas residence time at 1000°C: 1 second
- residual oxygen in flue gas: 6% minimum.

STEP 1: ASSUMPTIONS

Calculations involving incineration of biomedical waste are usually based on a number of assumptions. In this example, the chemical empirical formula, the molecular weight and the higher heating value of each of the main components of biomedical waste have been taken as follows:

1. Chemical Characteristics

Component	Empirical Formula	Molecular Weight	Higher Heating Value (kJ/kg)
Tissue	$C_5 H_{10} O_3$	118.1	20,471[8]
Cellulose, Swabs, Bedding	$C_6 H_{10} O_5$	162.1	18,568[7]
Plastics-polyethylene 96%	$(C_2 H_4)_x$	28.1*	46,304[7]
-PVC 4%	$(C_2 H_3 Cl)_x$	62.5*	22,630[7]
Sharps	Fe	55.8	0
Moisture	H_2O	18.0	0
Disinfectants, Alcohols	$C_2 H_5 OH$	46.1	30,547[7]
Glass	$Si O_2$	60.1	0

* Molecular weight of Monomer

2. Input temperature of waste, fuel and air is 15.5°C.

3. Air contains 23% by weight O_2 and 77% by weight N_2.

4. Air contains 0.0132 kg H_2O/kg dry air at 60% relative humidity and 26.7°C dry bulb temperature.

5. For any ideal gas 1 kg mole is equal to 22.4 m^3 at 0°C and 101.3 kPa.

6. Latent heat of vaporization of water at 15.5°C is 2460.3 kJ/kg.

STEP 2: CALCULATION OF MATERIAL INPUT

Table 3A on page 9 provides a range of characteristics for various types of biomedical waste. Sound judgement should be exercised when making use of this table to assign the component weight percent required to perform heat and material balance calculations. The red bag waste is typically composed of mainly human tissue as indicated in table 3A. Based on an input of 30% of 100 kg/h (ie. 30 kg/h), the red bag was assumed to have the following composition.

Tissue (dry)	$C_5 H_{10} O_3$	0.15 x 30 =	4.5 kg/h
Water	H_2O	0.8 x 30 =	24.0 kg/h
Ash	-	0.05 x 30 =	1.5 kg/h
	Total Red Bag		30.0 kg/h

The yellow bag waste input is 70% of 100 kg/h (i.e 70 kg/h) and was assumed to have the following composition:

Polyethylene	$(C_2 H_4)_x$	0.35 x 70 =	24.50 kg/h
Polyvinyl chloride	$(C_2 H_3 Cl)_x$	0.04 x 70 =	2.80 kg/h
Cellulose	$C_6 H_{10} O_5$	0.51 x 70 =	35.70 kg/h
Ash	-	0.1 x 70 =	7.0 kg/h
	Total Yellow Bag		70.00 kg/h

STEP 3: CALCULATION OF HEAT INPUT OF WASTES (kJ/h)

The HHV and heat input of each component are tabulated below.

Component	HHV kJ/kg	Input kg/h	Total Heat in kJ/h
$C_5 H_{10} O_3$	20,471	4.5	92,119.5
H_2O	0	24.0	0.0
$(C_2 H_4)_x$	46,304	24.5	1,134,448.0
$(C_2 H_3 Cl)_x$	22,630	2.8	63,364.0
$C_6 H_{10} O_5$	18,568	35.7	662,877.6
Ash	0	8.5	0.0
		100.0	
	Total Heat in From Wastes		1,952,809.1 kJ/h

STEP 4: DETERMINATION OF STOICHIOMETRIC OXYGEN FOR WASTES

The total stoichiometric (theoretical) amount of oxygen required to burn (oxidize) the waste is determined by the chemical equilibrium equations of the individual components of the biomedical waste and are provided in the following:

1.	$C_5H_{10}O_3$ +	$6O_2$ =	$5CO_2$ +	$5H_2O$	
	118.1	6(32)	5(44)	5(18)	
	1.0	1.63	1.86	0.76	
Tissue (as fired)	4.5	7.32	8.38	3.43	
2.	$(C_2H_4)_x$ +	$3O_2$ =	$2CO_2$ +	$2H_2O$	
	28.1	3(32)	2(44)	2(18)	
	1.0	3.43	3.14	1.29	
Polyethylene (as fired)	24.5	83.7	76.7	31.4	
3.	$2(C_2H_3Cl)_x$ +	$5O_2$ =	$4CO_2$ +	$2H_2O$ +	$2HCl$
	2(62.5)	5(32)	4(44)	2(18)	2(36.5)
	1.0	1.28	1.41	0.29	0.58
PVC (as fired)	2.8	3.58	3.94	0.81	1.64
4.	$C_6H_{10}O_5$ +	$6O_2$ =	$6CO_2$ +	$5H_2O$	
	162.1	6(32)	6(44)	5(18)	
	1.0	1.19	1.63	0.56	
Cellulose (as fired)	35.7	42.3	58.1	19.8	

The stoichiometric oxygen required to burn the combustible components of the biomedical waste (67.5 kg/h) is 136.9 kg/h O_2 (sum of 7.32, 83.7, 3.58, and 42.3).

STEP 5: DETERMINATION OF AIR FOR WASTE BASED ON 150% EXCESS

From Step 4, stoichiometric oxygen is 136.9 kg/h. Therefore,

$$\text{stoichiometric air} = 136.9 \times \frac{100}{23} = 595.2 \text{ kg/h air}$$

Total air required for waste (at 150% excess) = (1.5 x 595.2) + 595.2 = 1488 kg/h

STEP 6: MATERIAL BALANCE

Total Mass In

Waste	=	100.0 kg/h
Dry air	=	1488.0 kg/h
Moisture in air	=	19.6 kg/h (1488 x 0.0132)
Total Mass In	=	1607.6 kg/h

Total Mass Out (assuming complete combustion)

A. Dry Products from waste

Air supplied for waste	=	1488.0 kg/h
Less stoichiometric air for waste	=	595.2 kg/h
Total excess air	=	892.8 kg/h or 150%
Add nitrogen from stoichiometric air 0.77 x 595.2	=	458.3 kg/h
Sub-Total		1351.1 kg/h
Add total CO_2 from combustion:		
CO_2 formed from $C_5 H_{10} O_3$	=	8.38 kg/h
CO_2 formed from $(C_2 H_4)_x$	=	76.70 kg/h
CO_2 formed from $(C_2 H_3 Cl)_x$	=	3.94 kg/h
CO_2 formed from $C_6 H_{10} O_5$	=	58.10 kg/h
Total Waste Dry products		1498.22 kg/h

B. Moisture

H_2O in the waste	=	24.0 kg/h
H_2O from combustion reactions	=	55.44 kg/h
H_2O in combustion air	=	19.6 kg/h
Total Moisture		99.04 kg/h

C. Ash Output 8.5 kg/h

D. HCl formed from Wastes

HCl formed from $(C_2 H_3 Cl)_x$ = 1.64 kg/h

Total Mass Out = sum of (A,B,C,D)

= 1607.4 kg/h

STEP 7: HEAT BALANCE

a. Total Heat in From Waste (Qi)

Qi = 1,952,809.1 kJ/h (see Step 3)

b. Total Heat out Based on Equilibrium Temperature of 1100°C (Qo)

i) radiation loss = 5% of total heat available
= 0.05 x 1,952,809.1
= 97,640.0 kJ/h

ii) heat to ash = mCpdT
= (8.5)(0.831)(1084.5)
= 7660.4 kJ/h

where m = weight of ash
= 8.5 kg/h
Cp = mean heat capacity of ash
= 0.831 kJ/kg.°C (assumed average value)
dT = temperature difference
= (1100-15.5)°C
= 1084.5°C

iii) heat to dry combustion
products = mCpdT
= (1498.22)(1.086)(1084.5)
= 1,764,554.1 kJ/h

where m = weight of combustion products
= 1498.22 kg/h
Cp = mean heat capacity of dry products
= 1.086 kJ/kg°C (assumed average value)
dT = (1100-15.5)°C
= 1084.5°C

iv) heat to moisture = (mCpdT) + (mHv)

(mCpdT)+(mHv)= (99.04 x 2.347 x 1084.5)+(99.04 x 2460.3)
= 252,088.6 + 243,668.1
= 495,756.7 kJ/h

where m = weight of water
= 99.04 kg/h
Cp = mean heat capacity of water
= 2.347 kJ/kg.°C
dT = (1100-15.5)°C
= 1084.5°C
Hv = latent heat of vapourization of water
= 2460.3 kJ/kg

Total Heat Out (Qo) = sum of (i, ii, iii, iv)
= 2,365,611.2 kJ/h

Net Balance: = Qi - Qo
= 1,952,809.1 - 2,365,611.2
= -412,802.1 kJ/h (deficiency)
Auxiliary fuel must be supplied to achieve design temperature of 1100°C.

STEP 8: REQUIRED AUXILIARY FUEL TO ACHIEVE 1100°C

i) total heat required
from fuel = 412,802.1 + 5% radiation loss
= 433,442.2 kJ/h

ii) available heat (net) from natural gas at 1100°C and 20% excess air = 15,805.2 kJ/m^3[8]

Natural gas required = $\frac{433,442.2}{15,805.2}$ m^3/h
= 27.42 m^3/h

STEP 9: PRODUCTS OF COMBUSTION FROM AUXILIARY FUEL

i) Dry Products From Fuel
at 20% Excess Air = $\frac{16.0 \text{ kg}}{m^3 \text{ fuel}}$[8] x 27.42 m^3/h
= 438.7 $\frac{kg}{h}$

ii) Moisture From Fuel = $\frac{1.59 \text{ kg}}{m^3 \text{ fuel}}$[8] x 27.42 m^3/h

STEP 10: SECONDARY CHAMBER VOLUME REQUIRED TO ACHIEVE ONE SECOND RESIDENCE TIME AT 1000°C

i) Total Dry Products
from waste + fuel = 1498.22 kg/h + 438.7 kg/h
= 1936.9 kg/h

Assuming dry products have the properties of air and using the ideal gas law, the volumetric flow rate of dry products (dp) at 1000°C (Vp) can be calculated as follows:

$$Vp = 1936.9 \frac{\text{kg dp}}{\text{h}} \times \frac{22.4 \text{ m}^3}{29 \text{ kg dp}} \times \frac{1273\text{K}^*}{273\text{K}} \times \frac{1 \text{ h}}{3600\text{s}}$$

$= 1.94 \text{ m}^3/\text{s}$

ii) Total Moisture
from waste + fuel = 99.04 kg/h + 43.6 kg/h
= 142.6 kg/h

Using the ideal gas law, the volumetric flow rate of moisture at 1000°C (Vm) can be calculated as follows:

$$Vm = 142.6 \frac{\text{kg } H_2O}{\text{h}} \times \frac{22.4 \text{ m}^3}{18 \text{ kg } H_2O} \times \frac{1273\text{K}}{273\text{K}} \times \frac{1 \text{ h}}{3600\text{s}}$$
$= 0.23 \text{ m}^3/\text{s}$

Total Volumetric Flow Rate = sum of (i, ii)
= 1.94 + 0.23
= 2.17 m^3/s

Therefore, the active chamber volume required to achieve one second retention is 2.17 m^3 ('dead' areas - with little or no flow should not be included in the retention volume). It should be noted that in sizing the secondary chamber to meet the one second retention time required, the length of chamber should be calculated from the flame front to the location of the temperature sensing device.

* K = °C + 273

STEP 11: RESIDUAL OXYGEN IN THE FLUE GAS

The residual oxygen ($\%O_2$) can be determined using the following equation:

$$EA \text{ (excess air)} = \frac{\% O_2}{21\% - \%O_2}$$

$$\text{Therefore, } \frac{150}{100} = \frac{\% O_2}{21\% - \%O_2}$$

$$\%O_2 = 12.6\%$$

APPENDIX B:

CALCULATION OF THE REYNOLDS NUMBER

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The Reynolds Number (Re) can be determined as follows:

$$Re = \frac{VD}{Ki}$$

where V = average velocity, m/s
D = diameter (or equivalent diameter) of flow stream, m
Ki = kinematic viscosity, m^2/s

As an example of this calculation, assume a secondary chamber has an internal diameter of 2 m. The gas flow is at a temperature of 1000°C, and is at a velocity of 10 m/s. From Figure 5, $K = 140 \times 10^{-6}$ at 1000°C. Therefore:

$$Re = \frac{VD}{Ki}$$

$$= \frac{10\ m/s \times 2\ m}{140 \times 10^{-6}\ m^2/s}$$

$$= 143{,}000.$$

This is greater than the critical Re (10,000) and turbulence can be assumed to be adequate.

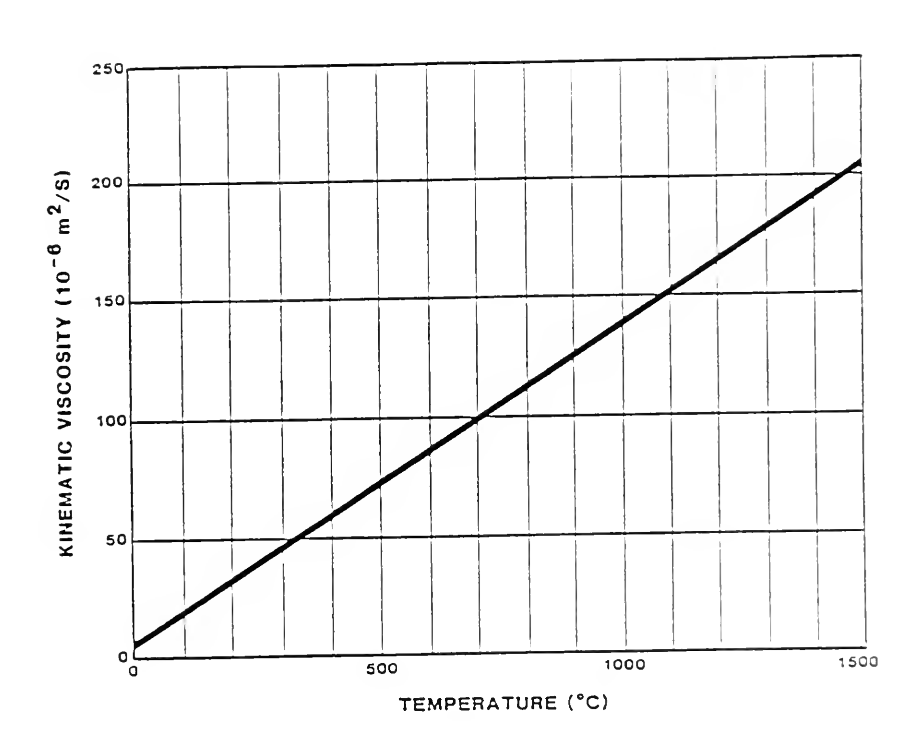


FIGURE 5: KINEMATIC VISCOSITY OF AIR VERSUS TEMPERATURE

